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THERMAL LOSSES AT THE BOILER

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AN INVESTIGATION OF THE THERMAL LOSSES AT THE BOILER RESULTING FROM THE IMPROPER MIXTURE OF THE COMBUSTIBLE GASES.

by

CHARLES Henry WILLIAMS

A Thesis Submitted for the Degree of

MECHANICAL ENGINEER.

UNIVERSITY OF WISCONSIN

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The results of the following tests made at the boiler plant of the Madison Gas and Electric Company were obtained in an endeavor to decrease the percentage of thermal losses, by the proper regulation of the amount of air admitted to the grates and by regulating the intensity of draft to obtain a more complete combustion of the fuel.

The tests consisted of twenty sets, ten being made under different conditions of load, at different hours of the day, and without the knowledge of the fireman in charge; the other ten being made after the results of the first ten were determined, changes in the intensity of draft and changes in the amount of air passing the grates being made by changing the position of the damper in the stack and by opening and closing the ash pit doors, as the results of each succeeding test were ascertained.

The Madison plant offers excellent facilities for

checking the results of a test because a comprehensive report is made for each twelve hour shift, these reports showing the number of pounds of coal used, the number of pounds of ash produced, the number of cubic feet of water evaporated and the number of kilo-watts generated, together with the watts per pound of coal, pounds of water per pound of coal and boiler efficiency, and the readings of the instruments necessary to determine these quantities being taken regularly twice every day, the errors liable to occur in these tests were lessened.

A short description of the apparatus, and the manner of handling it, for the collection of the samples and for making the analysis of the gases will be given.

The boilers on which the tests were made were two 250 H. P. Hazelton or Porcupine Water Tube Boilers and were hand fired. These boilers occupy a floor space of but 126 1/2 square feet each, they present 2906 square feet of heating surface or 11.62 square feet per horse power and have 60.9 square feet of grate surface.

Besides air being admitted to the furnace from below the grates through the ash pit doors each boiler was supplied with numerous passage ways, of four inch cross sectional area each. These passage ways were supplied with dampers which, on being opened admitted air to the furnace

above the grate bars, first leading it through a passage way, through the fire brick, enclosing the furnace, so that the air on entering the furnace and coming in contact with the combustible gases had reached a high temperature.

In the hood of the boiler, twenty-five feet above the grates, and just above the top row of tubes, a hole was tapped to admit a tube for the collection of the samples to be tested.

This tube for the collection of the samples of gas was made as is shown in the accompanying sketch. (A) is a 1/4 inch brass tube, 3 1/2 feet long, surrounded by a water jacket which is formed by means of a 3/4 inch pipe (B), and a 1 3/4 inch pipe (C), fitted with reducing couplings on the ends as is shown in the sketch.

The water enters at (X) being supplied by a 1/2 inch hose attached to a hydrant, flows to the end of the pipe (B), as shown by the arrows, then enters the pipe (B) and flows back to the outlet at (Y) keeping the temperature of the collecting pipe within such limits that there is no danger of any change taking place in the gas while it is being led through the collecting pipe on account of chemical action between the gas and the pipe itself. Such a change might occur should the gas pass through a metal

pipe heated to a high temperature.

To store the gas six galvanized iron cans were used of two liters capacity each; these cans having a way-cock in the side near the bottom and a way-cock on the top, the top being of a conical shape below the cock.

A rubber hose fitted tightly to the collecting tube and to the top way-cock on the galvanized cans, gave a connection that facilitated the easy handling of the gas collecting apparatus.

Before a sample of the gas was taken from the hood, the tank, the connecting tube, and the collecting pipe were all completely filled with water to drive out all the air; then the collecting pipe was introduced into the hood and the cock at the end of the tube opened.

A piece of asbestos was fitted around the tube on the opening in the hood so that no air could be admitted at that point.

When the cocks on the tank were opened the water ran out of the lower one and in doing so drew out a sample of gas, the free end of the tube meanwhile being moved around inside the hood.

The tanks were allowed to drain out two thirds of their water, collecting one and a third liters of the gas

for each sample.

The tanks were now tightly sealed and allowed to stand in the room in which they were to be analyzed for one hour so that when the samples were drawn off their volume would not be changed by any change of temperature.

The apparatus used for the analysis of the gas was that known as the Orsat Testing Apparatus, and the accompanying sketch and description explains the method used in making the analysis.

The apparatus consists of a measuring tube (A) graduated to cubic centimeters and surrounded by a water jacket (E) to prevent changes in volume on account of changes in temperature.

Three pipettes (B. C. D.) connected to the tube (K) by means of short pieces of rubber hose, having pinch cocks placed just above the glass necks.

A three-way cock (H) opening to the connecting tube, the tank containing the sample of gas, and to the air; a leveling bottle (G) which has a pinch cock at (F).

The reagents in the pipettes are adjusted in the capillary tubes to a marked point on the glass by opening the pinch cock (F) and the ones above the capillary tubes--one at a time and lowering the leveling bottle.

After the reagents are all adjusted, the measuring bottle and connecting tube are completely filled with water by raising the leveling bottle until water runs out of the three way-cock when the apparatus is ready to receive a sample of gas for analysis.

A sample of the gas is drawn over into the measuring tube and then by means of the three way-cock it is expelled into the air and a second sample is drawn out--a little over one hundred cubic centimeters being drawn into the measuring tube, the three-way cock being closed against the connecting tube the gas was compressed to one hundred cubic centimeters by slightly raising the leveling bottle (F) being open. The three-way cock was then opened to the air for a second, while (F) was open, and the water in the bottle and the measuring tube brought to the same line which coincided with the one hundred mark on the C.C. scale, after the tube had been allowed to drain one minute. The pinch cock between the connecting tube and the first pipette was then opened and the gas forced into the first pipette displacing the reagent in the front part and laid bare numerous small glass tubes which presented a large surface for the reagent to act upon the gas.

This first pipette contained potassium hydrate

which has the property of absorbing carbon dioxide.

The gas was passed back and forth a number of times until all the carbon dioxide was absorbed when the remainder was drawn back into the measuring tube and the tube allowed to drain one minute.

The water in the measuring tube and in the bottle was brought to the same level and then a reading taken.

The difference between this reading and the initial reading (one hundred cubic centimeters) shows the amount of carbon dioxide present in parts of one hundred or the percent of carbon dioxide present.

The gas is now forced into the second pipette which contained an alkaline solution of potassium pyrogallate for the absorption of oxygen.

The same process was gone through with in the absorption of oxygen as in the case of carbon dioxide, a longer time being necessary for the complete absorption of oxygen.

The gas was again drawn back into the measuring tube and its volume measured as in the case of carbon dioxide and the difference in the reading then obtained and in that obtained after the absorption of carbon dioxide shows the percent of oxygen present.

Finally the remaining gas was forced into the third pipette containing cuprous chloride for the absorption of carbon monoxide and was passed back and forth until no more absorption took place.

Then the gas was returned to the measuring tube and the volume determined and the volume subtracted from the volume obtained after the absorption of oxygen gave the amount of carbon monoxide present.

The immediate results sought for in the analysis, were first, the determination of the completeness of the combustion, especially the amount of air which had been used or the pounds of air per pound of coal, and second the amount of heat that had passed up the chimney.

Taking up the analysis, for convenience of comparison the results of the two sets will be carried on in parallel columns-- a full explanation being given with the first set and a somewhat abbreviated form given in the second set but following the first in every particular.

The first set as was stated before have to do with an average of all the tests of the samples taken during the preliminary work and the second set shows the average of all the results taken after errors in the mode of handling the furnaces had been determined and rectified as far as the ability of the operators was able to rectify them.

The following is data taken from analysis.

First Set			Second Set.		
%CO_2	%O	%CO	%CO_2	%O	%CO
4.	13.2	3.2	7.2	12.1	.51
4.75	14.8	2.3	8.2	11.1	.34
6.4	11.5	3.52	8.8	12.	.03
5.	14.8	2.2	9.2	11.1	.01
3.6	10.5	5.52	12.5	7.3	.000
2.25	15.3	3.18	12.6	7.2	.000
3.1	15.7	2.4	9.2	10.3	.01
5.	12.8	3.08	9.1	12.1	.000
2.	16.2	3.18	9.	12.1	.000
4.5	12.	4.52	7.2	13.	.000

Taking the average of all the results for the two sets of tests give,

First Set   Second Set.

Carbon Dioxide = CO_2 = 4.06% CO_2 = 9.3%

Oxygen = O = 13.68"   O = 10.82"

Carbon Monoxide = CO = 3.31"   CO = .09"

Nitrogen = N = 78.95"   N = 79.79"

The atomic weights of Oxygen = 16

" " " " Carbon = 12

The weights of one liter of CO_2 = 1.97 grams

" " " " " " O = 1.43 "

" " " " " " CO = 1.25 "

To find the number of pounds of air used per pound of coal, first find the number of grams of each constituent in one hundred liters of the flue gas and from this the weight of carbon and the weight of oxygen.

4.06 × 1.97 = 7.998 grams CO_2 9.3 × 1.97 = 18.32 grams CO_2

But 32/44 $\left(\frac{O_2}{CO_2}\right)$ is oxygen

32/44 × 7.998 grams = 5.81 grams O   32/44 × 18.32 = 13.3 grs.O

7.998 − 5.91 = 2.188 grams carbon   18.32 − 13.3 = 5.02 " carbon

From the analysis the weight of free oxygen is,

13.68 × 1.43 = 19.56 grams O   10.82 × 1.43 = 15.45 grs.O

The weight of carbon and oxygen in the CO is,

3.31 × 1.25 = 4.13 grams CO   .9. × 1.25 = 1.125 grs.CO

But $\frac{16}{28}$ $\left(\frac{O}{CO}\right)$ is oxygen.

16/28 × 4.13 = 2.35 grams oxygen   16/28 × 1.125 = .644 grs.O

4.13 − 2.35 = 1.78 grams carbon   1.125 − .644 = .481 grs. C.

Adding the quantities of Carbon together and the quantities of oxygen together

Oxygen	Carbon	Oxygen	Carbon
5.81	2.18	13.2	5.02
19.56	1.78	15.45	.481
2.35		.644	
27.72 grams O	3.96 grams C.	29.294 grs.O	5.501 grs.C

That is 27.72 grams oxygen to 3.96 grams carbon, and as air is made up of 23.16% oxygen by weight this will be equivalent to 120 grams of air to 3.96 grams of carbon or 120 pounds of air to 3.96 pounds of carbon or 30.3 pounds of air to one pound of carbon	. 29.294 grs.O to 5.501 grs C 127 grs.or pounds air to 5.501 grs. or pounds carbon 23.1 pounds of air to one pound of carbon

The analysis of the coal showed 80.1 % carbon so the above proportions are equivalent to ,

24.21 pounds of air per pound of coal, which is beyond the limits of good practise.	18.5 pounds of air per pound of coal; which is good practise.

To find the quantity of heat passing up the chimney. The following investigation will be carried on in connection with the second set of tests that is after the remedies had been applied to promote the more complete combustion.

Find the volume of gas generated when one kilogram of coal has been burned to produce the gas as previously

analyzed.

The chemical analysis of the coal used during the tests was as follows:

Carbon	80.10 %	Sulphur	.65
Hydrogen	4.34	Ash	5.40
Nitrogen	1.07	Phosphorus	.01
Oxygen	8.41		100.00%

Total Volatile Matter	30.49 %
Moisture	1.03
Fixed Carbon	64.1

Referring to the coal analysis there was in one kilogram of coal 801 grams of carbon, and of this suppose 776 grams are burned 25 grams going into the ash.

Referring back to the analysis to the number of grams of carbon from the carbon dioxide and the carbon monoxide

$\frac{502}{550}$ of the 776 grams produced 705 grams CO_2

$\frac{48}{550}$ " " " " " 71 " CO

From 5.02 grams of carbon were produced 9.3 liters of carbon dioxide therefore 705 grams would produce 1030 liters carbon dioxide.

$$5.02 : 705 :: 9.3 : x \qquad x = 1310$$

In the same way 71 grams carbon would produce 132 liters carbon monoxide,

481 : 71 :: .09 : x   x = 132.

The volume of oxygen is found from the proportion,

9.3 : 10.82 :: 1310 : x   x = 1512

In the same way the volume of nitrogen is found,

9.3 : 79.79 :: 1310 : x   x = 11239 liters N.

Under these conditions with one kilo of coal there were produced,

1.31	cubic	meters	of	carbon dioxide
.013	"	"	"	carbon monoxide
1.512	"	"	"	Oxygen
11.24	"	"	"	Nitrogen.

The quantity of heat carried away by each gas is equal to its rise in temperature times its weight times its specific heat.

The average temperature of the air entering the grates was $52^{\circ}F = 11^{\circ}C$ and the average pyrometer reading was $600^{\circ}F = 320^{\circ}C$ the rise in temperature being $320^{\circ} - 11^{\circ} = 309^{\circ}C$.

By means of the wet and dry bulb thermometer the air was shown to be 50%saturated.

The following table shows the specific heat, the weight of a cubic meter and the product of specific heat

times weight of the several gases.

Gas	Specific Heat	Wt. of Cu. M (Kg)	Sp. heat times weight of Cu.M.
CO_2	.234	1.97	.463
CO	.245	1.25	.308
O	.217	1.43	.311
Aqueous Vapor	480	.80	.387
N.	.244	1.26	.306

The heat carried away then is as follows:

CO_2 1.310 × 309 ×.463 = 187.417 C
CO .013 × 309 ×.308 = 1.247
O 1.512 × 309 ×.311 = 145.30
N. 11.240 × 309 ×.306 = 1062.84
14.075

The aqueous vapor which comes from the moisture in the coal, from the combustion of the hydrogen in the coal and the air entering the grates also carries away heat, the amount of which is calculated as follows.

The moisture in the air corresponding to 11°C. would be if completely saturated 10 grams per cubic meter but the air is 50% saturated. The quantity is then the volume of air entering per kilogram of coal times the

moisture contained in it.

$$14.075 \times 10 \times .50 = 70.375 \text{ or } .70375 \text{ kg.}$$

The moisture in the coal is 1.03% = .0103 kg.
The hydrogen is 4.345% = .0435 kg. and the amount of water this forms in burning is equal to nine times its weight,
$.0435 \times 9 = .3915$ kg.

Then the weight of the aqueous vapor passing up the chimney per. kg. of coal is $.70375 + .0103 + .3975 = 1.105$ kg. and the quantity of heat that this carried away was equal to,

$$1.105 \times 309 \times .48 = 163.89 \text{ calories.}$$

The total heat then passing up the chimney equals,
$1396.8 + 163.8 = 1560.6$ calories.
The heat of combustion of the coal was 8060 calories, therefore the percent of heat going up the chimney and escaping equaled $\frac{1560.69}{8060} = 19.49\%$.

The comparative results of the two sets of tests for the determination of the quantity of air entering the grates shows for the first set 24.21 pounds of air per pound of coal and for the second set 18.5 pounds per pound of coal. The theoretical quantity of air necessary for the complete combustion of the fuel requires 11.54 pounds of air per pound of carbon, so for each pound of

coal there is a fixed amount of air necessary for the complete combustion varying as the percent of carbon varies in the different coals and it is our inability to convey this exact amount to the furnace that prevents our obtaining and maintaining perfect combustion.

Now in order to produce combustion carbon must unite with oxygen, which it does in certain unvarying proportions.

In the first stage of the combustion one part of the carbon unites with one part of the oxygen forming carbon monoxide and in that process about one-fourth of the latent energy stored in the coal is changed to heat and given up to the furnace; in the second stage the carbon monoxide absorbs another part of oxygen forming carbon dioxide and in that process the balance of the energy is converted into heat.

If insufficient air is admitted the carbon monoxide cannot find enough oxygen to complete its change to carbon dioxide.

This is the most wasteful condition for the largest part of heat is generated in the second stage of combustion; but the most common case is where too much air is admitted, then the results of the combustion are poor because

a large amount of air is passing through the fire whose oxygen cannot find carbon to unite with. In which case the surplus oxygen is heated to the same temperature as the escaping gases absorbing the heat already generated and taking it away from the water.

Returning to the comparative results of the two sets of tests it is evident that the quantity of air entering the grates has been decreased 23.67%.

Now taking the watts generated per pound of coal----- all day average----- for the ten days preceeding the first set of tests and for the ten days following the second set of tests, the plant records show an average of 172.6 watt hours per pound of coal for the first set and 189.16 watts per pound of coal for the second set, which shows an increase of plant efficiency of 9.59%.

The average daily coal consumption for the ten days preceeding the first set was 24915 pounds or 12.45 tons and 9.59% of this gives for a saving on the coal pile 1.19 tons, which at $3.55 a ton, the price paid for the coal, shows a direct saving of Four dollars and twenty two cents a day as a result of the increased efficiency.

If we know the amount of carbon dioxide present in the escaping gas we know whether the combustion is being

carried on within economical limits or whether as is very often the case the amount of air is entirely out of proportion to the amount of coal being consumed.

By means of chemical analysis as used in the foregoing tests we can determine at any time what the conditions of combustion are but this gives us information for the time only during which the samples of gas are being taken--- a few minutes time being sufficient to entirely change the condition, but these determinations though irregular prove to be of great value and have led to the invention of mechanical devices, which indicate continuously the exact percentage of carbon dioxide present in the escaping gases.

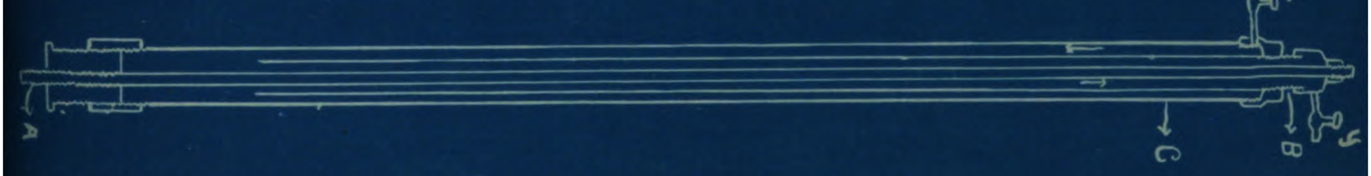
The operation in general is as follows;by means of a small pipe the gas is passed from the stack through a glass globe suspended in air on one arm of a balance where it is weighed.

The weighing of the gas is possible,because the specific gravity of all the gases passing through the instrument is the same except that of CO_2 which is about 50 percent greater, so the greater the proportion of CO_2 the heavier the gas will be and the more the pointer will indicate; and the apparatus being in constant operation

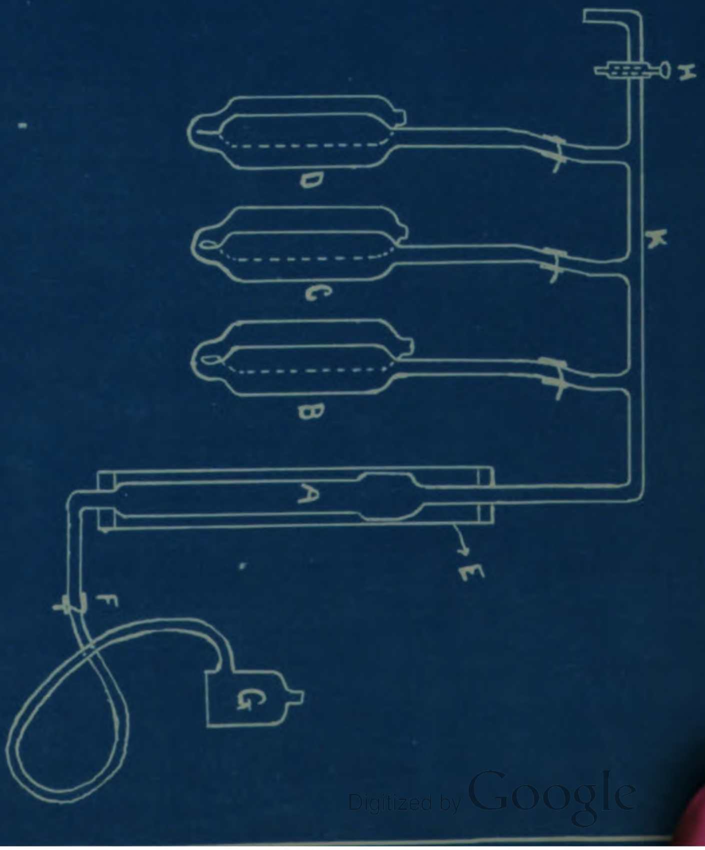
any chage can be seen at once, so the instrument acts as a guide to the fireman to show him when he is getting good or poor results from the combustion of the coal.

In the same way that the recording steam guage serves to keep a healthy rivalry among the firemen-- each trying to get the best line-- and in doing so exerting greater care in firing, an apparatus such as described above with a recording apparatus would not only give a valuable record of the work of the men handling the boilers but would also enable them to do the firing with a better understanding of the economy gained by the proper regulation of their furnaces, and it is the opinion of those in charge of the Madison plant that the use of such an apparatus would lead to better economy and consequently they intend to put such an apparatus into service.

Collecting Tube



Orsat Testing Apparatus



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